

METAL-POOR, STRONGLY STAR-FORMING GALAXIES IN THE DEEP2 SURVEY: THE RELATIONSHIP BETWEEN STELLAR MASS, TEMPERATURE-BASED METALLICITY, AND STAR FORMATION RATE

CHUN LY^{1,4}, JANE R. RIGBY¹, MICHAEL COOPER², AND RENBIN YAN³*Draft version March 10, 2015*

ABSTRACT

We report on the discovery of 28 $z \approx 0.8$ metal-poor galaxies in DEEP2. These galaxies were selected for their detection of the weak [O III] λ 4363 emission line, which provides a “direct” measure of the gas-phase metallicity. A primary goal for identifying these rare galaxies is to examine whether the fundamental metallicity relation (FMR) between stellar mass, gas metallicity, and star formation rate (SFR) holds for low stellar mass and high SFR galaxies. The FMR suggests that higher SFR galaxies have lower metallicity (at fixed stellar mass). To test this trend, we combine spectroscopic measurements of metallicity and dust-corrected SFRs, with stellar mass estimates from modeling the optical photometry. We find that these galaxies are 1.05 ± 0.61 dex above the $z \sim 1$ stellar mass–SFR relation, and 0.23 ± 0.23 dex below the local mass–metallicity relation. Relative to the FMR, the latter offset is reduced to 0.01 dex, but significant dispersion remains (0.29 dex with 0.16 dex due to measurement uncertainties). This dispersion suggests that gas accretion, star formation and chemical enrichment have not reached equilibrium in these galaxies. This is evident by their short stellar mass doubling timescale of $\approx 100^{+310}_{-75}$ Myr that suggests stochastic star formation. Combining our sample with other $z \sim 1$ metal-poor galaxies, we find a weak positive SFR–metallicity dependence (at fixed stellar mass) that is significant at 94.4% confidence. We interpret this positive correlation as recent star formation that has enriched the gas, but has not had time to drive the metal-enriched gas out with feedback mechanisms.

Subject headings: galaxies: abundances — galaxies: distances and redshifts — galaxies: evolution — galaxies: ISM — galaxies: photometry — galaxies: starburst

1. INTRODUCTION

The chemical enrichment of galaxies, driven by star formation and modulated by gas flows from supernova and cosmic accretion, is key for understanding galaxy formation and evolution. The primary approach for measuring metal abundances is spectroscopy of nebular emission lines. These emission lines can be observed in the optical and near-infrared at $z \lesssim 3$ from the ground (e.g., Kobulnicky & Kewley 2004; Erb et al. 2006; Maiolino et al. 2008; Hainline et al. 2009; Hayashi et al. 2009; Mannucci et al. 2009; Moustakas et al. 2011; Rigby et al. 2011; Nakajima et al. 2012; Henry et al. 2013a; Momcheva et al. 2013; Pirzkal et al. 2013; Zahid et al. 2011; Ly et al. 2014; Troncoso et al. 2014; de los Reyes et al. 2015) and space (e.g., Atek et al. 2011; van der Wel et al. 2011; Xia et al. 2012; Henry et al. 2013b; Whitaker et al. 2014b), and the *James Webb Space Telescope* will extend this to $z \sim 6$.

The most reliable metallicity measurements are made by measuring the flux ratio of the [O III] λ 4363 line against [O III] λ 5007. The technique is called the T_e method because it determines the electron temperature (T_e) of the gas, and hence the gas-phase metallicity (Aller 1984). However, the detection of [O III] λ 4363 is difficult, as it is weak, almost undetectable in metal-rich galaxies. Only 0.3% of the Sloan Digital Sky Survey (SDSS) has de-

tected [O III] λ 4363 at signal-to-noise (S/N) ≥ 2 (Izotov et al. 2006).

Efforts have been made to increase the number of galaxies with direct metallicities in the local universe (e.g., Brown et al. 2008; Berg et al. 2012; Izotov et al. 2012), and at $z \gtrsim 0.2$ (Hoyos et al. 2005; Kakazu et al. 2007; Hu et al. 2009; Amorín et al. 2014a,b; Ly et al. 2014, hereafter Ly14); however, the total sample size is ~ 145 (mostly in the local universe).

Using the DEEP2 Galaxy Redshift Survey (Davis et al. 2003; Newman et al. 2013), we are conducting studies that utilize [O III] λ 4363 detections in individual galaxies and from stacked spectra. In this paper, we focus on first results from individual [O III] λ 4363 detections in 28 galaxies. Our sample of 28 galaxies substantially increases the number of $z \geq 0.25$ galaxies with S/N ≥ 3 [O III] λ 4363 detections by 44% (64 to 92).

While the selection function is biased toward metal-poor galaxies, this galaxy population is of significant interest for understanding galaxy evolution. Their low metallicity suggests that they are either (1) in their earliest stages of formation, (2) accreting metal-poor gas, or (3) undergoing significant metal-enriched gas outflows. Metal-poor galaxies have been poorly studied due to the difficulty of identifying them. Thus, the majority of previous high- z metallicity studies have only used strong-line metallicity calibrations. These calibrations are problematic for high- z galaxies due to suspected differences in the physical conditions of the interstellar gas (e.g., Liu et al. 2008; Kewley et al. 2013a,b), but see also Juneau et al. (2014) for a different interpretation. These differences, if present, may be incorrectly interpreted as evolution in the metal content. Thus, obtaining T_e -based metallicities

¹ Observational Cosmology Laboratory, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA;

² Center for Galaxy Evolution, Department of Physics and Astronomy, UCI, Irvine, CA, USA

³ Department of Physics and Astronomy, University of Kentucky, Lexington, KY, USA

⁴ NASA Postdoctoral Fellow.

ties at high redshifts is the next logical step, and these [O III] λ 4363 detections can potentially be used to recalibrate the strong-line diagnostics.

While the T_e method is affected by properties of the ionized gas (e.g., optical depth, density, ionization parameter, non-equilibrium electron energy; Nicholls et al. 2014), such effects also apply to strong-line diagnostics as Nicholls et al. (2014) demonstrated. Thus, while the T_e method is less “direct” than was initially determined (Seaton 1954), measuring the electron temperature currently remains the preferred way to determine gas metallicities.

In this paper, we focus on the relationship between stellar mass, gas-phase metallicity, and SFR for our sample of 28 metal-poor galaxies. This relationship has received significant interest as Ellison et al. (2008) found that at a given stellar mass, lower-metallicity galaxies in the local universe tend to have higher SFRs. Thus, while the stellar mass–metallicity relation is tight (~ 0.1 dex; Tremonti et al. 2004), it may be a projection of a non-evolving three-dimensional relationship between stellar mass (M_*), gas-phase metallicity (Z), and SFR (e.g., Lara-López et al. 2010; Mannucci et al. 2010; Hunt et al. 2012).

However, the existence of a M_* – Z –SFR relation (dubbed the “fundamental metallicity relation” or “FMR”) remains controversial, as recent studies have yielded results that agree or disagree with predictions (see Salim et al. 2014 and de los Reyes et al. 2015 for a review). Moreover, the M_* – Z –SFR relation has yet to be tested with large samples of metal-poor ($Z \lesssim 0.25 Z_\odot$) galaxies, especially at higher redshift. The largest high- z metal-poor sample is that of Ly14 from the Subaru Deep Field (SDF; Kashikawa et al. 2004; Ly et al. 2007), which detected [O III] λ 4363 in 20 galaxies at $z \sim 0.4$ – 1 . In this study, they found evidence that galaxies with the highest specific SFR (SFR/ M_* , hereafter sSFR) were not necessarily more metal-poor. This result, based on 20 galaxies, requires further confirmation with our DEEP2 sample.

In this study, we compare our work with Andrews & Martini (2013) (hereafter AM13) who stacked $0.027 < z < 0.25$ SDSS spectra in bins of SFR and M_* to obtain average [O III] λ 4363 measurements. We note that the primary selection functions of AM13 (magnitude-limited) and our study (emission-line strengths) are different. In a forthcoming paper, we will follow the same approach as AM13 of stacking the spectra of a few thousand $z \sim 0.8$ DEEP2 galaxies, allowing for a more self-consistent comparison. For now, we investigate the M_* – Z –SFR relation with individual T_e metallicity measurements. Throughout this Letter, we adopt a cosmology with $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, and $h = 0.7$, a Chabrier (2003) initial mass function (IMF), and a solar metallicity of $12 + \log(\text{O}/\text{H}) = 8.69$.

2. THE SAMPLE

The DEEP2 Survey has surveyed $\sim 3 \text{ deg}^2$ over four fields using the DEIMOS multi-object spectrograph (Faber et al. 2003) on the Keck-II telescope. The survey has provided optical (≈ 6500 – 9000 \AA) spectra for $\sim 53,000$ galaxies brighter than $R_{\text{AB}} = 24.1$, and precise redshifts for $\sim 70\%$ of targeted galaxies. An overview of the survey can be found in Newman et al. (2013).

Using the fourth data release (DR4),⁵ we select 37,396 sources with reliable redshifts (quality flag ≥ 3). We consider those with spectral coverage that spans 3720–5010 \AA (rest-frame). This enable us to determine metallicity from oxygen and hydrogen emission lines ([O II] $\lambda\lambda$ 3726,3729, [O III] $\lambda\lambda$ 4363,4959,5007, and H β), and further limits the sample to 4,140 galaxies at $z = 0.697$ – 0.859 (average: 0.779).

We follow the approach of Ly14 that fits emission lines with Gaussian profiles using the IDL routine MPFIT (Markwardt 2009). Spectroscopic redshifts are used as priors for the location of emission lines. With measurements of emission-line fluxes and the noise in the spectra (measured from a 200 \AA region around each line), we select those with [O III] λ 4363 and [O III] λ 5007 detected at $S/N \geq 3$ and $S/N \geq 100$, respectively. This yields an initial sample of 54 galaxies. We inspect each spectrum and remove 26 galaxies from our sample, primarily because of contamination from OH sky-lines. This leaves 28 galaxies. One source (#21) was observed twice. The other spectrum also detected [O III] λ 4363 at lower S/N , so the better spectrum is used in our analysis. Compared to the previous DEEP2 sample (Hoyos et al. 2005), we confirmed two, thus 26 galaxies in our sample are newly identified. Detections of [O III] λ 4363 are shown in Figure 1, and galaxy properties are provided in Table 1. We illustrate in Figure 2 the emission-line luminosities, rest-frame equivalent widths (EWs), and $O_{32} \equiv [\text{O III}]/[\text{O II}]$ and $R_{23} \equiv ([\text{O II}] + [\text{O III}])/\text{H}\beta$ flux ratios (Pagel et al. 1979; McGaugh 1991), and compare our sample to local galaxies and other [O III] λ 4363-detected galaxies (Ly14).

2.1. Flux Calibration

The publicly released data of DEEP2 are not flux-calibrated, which is problematic for measuring the 4363-to-5007 ratio, and hence T_e . To address this limitation, we use proprietary IDL codes developed by Jeffrey Newman, Adam Walker, and Renbin Yan of the DEEP2 team. These codes take into account the overall throughput, quantum efficiency of the eight CCD detectors, apply coarse telluric corrections for atmospheric absorption bands, and use the R and I DEEP2 photometry to transform the spectrum to energy units. The DEEP2 team has demonstrated that the calibration is reliable at the 10% level when compared to SDSS stars observed by DEEP2.

3. DERIVED PROPERTIES

3.1. Dust Attenuation Correction from Balmer Decrements

To correct the emission-line fluxes for dust attenuation, we use Balmer decrement measurements. At $z \sim 0.8$, the existing DEEP2 optical spectra measure H β , H γ , and H δ . While these lines are intrinsically weak compared to H α ,⁶ our galaxies possess high emission-line EWs, which result in 22, 26, and 28 galaxies having H δ , H γ , and H β detected at $S/N \geq 10$, respectively. The significant detections enable dust attenuation measurements of $\sigma(A(\text{H}\alpha)) \approx 0.1 \text{ mag}$ (average from H γ /H β).

A problem encountered with Balmer emission lines is the underlying stellar absorption. Our examination of each spectrum reveal weak stellar absorption, making it

⁵ <http://deep.ps.uci.edu/dr4/home.html>.

⁶ H α is redshifted beyond the optical spectral coverage.

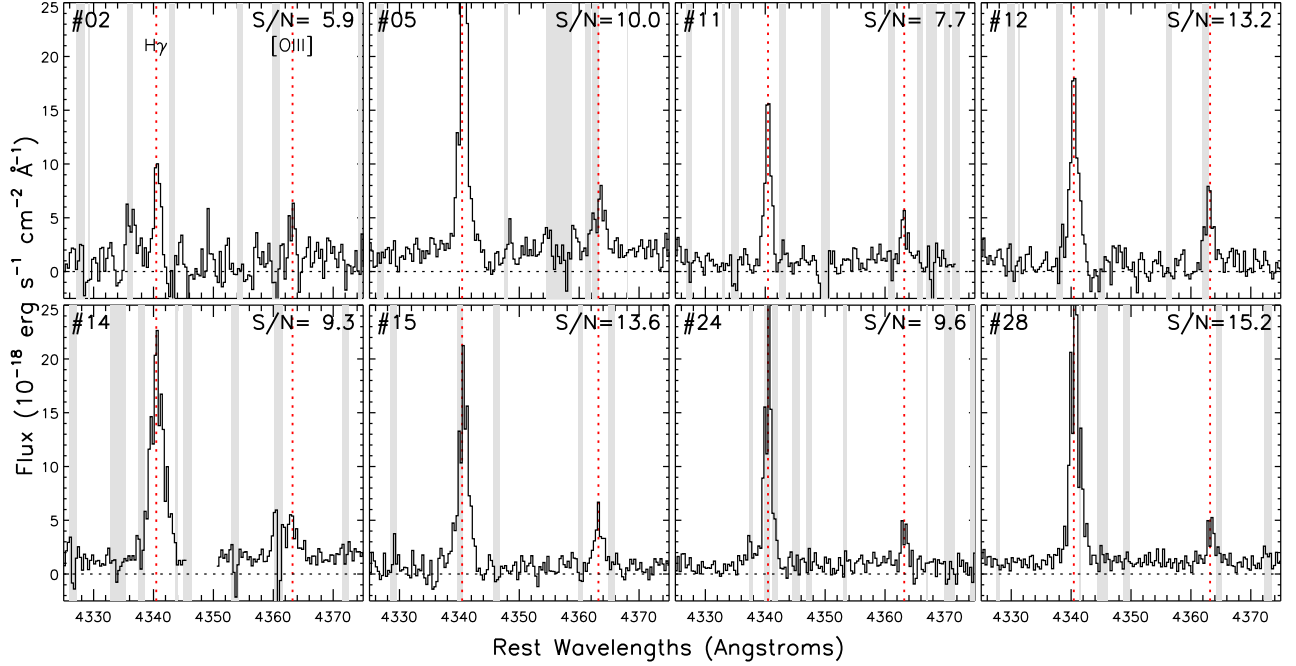


FIG. 1.— Detections of [O III] $\lambda 4363$ in $z \sim 0.8$ DEEP2 galaxies. The Keck/DEIMOS spectra for 8 of 28 galaxies are shown by the solid black lines, with vertical red dashed lines indicating the locations of $H\gamma \lambda 4340$ and [O III] $\lambda 4363$. OH skylines are indicated by the grey shaded regions. The signal-to-noise of [O III] $\lambda 4363$ detections is reported in the top right.

difficult to obtain reliable fits to the broad wings of absorption lines. To address this limitation, we stack our spectra. Here, the continuum (around each Balmer line) is normalized to one, and an average is computed with the exclusion of spectral regions affected by OH sky-line emission. Stellar absorption is detected in $H\delta$, and is consistent with an EW_{rest} correction of 1 Å. For our entire sample, we adopt an EW_{rest} correction of 1 Å for $H\beta$, $H\gamma$, and $H\delta$. With these corrections for stellar absorption, we illustrate the Balmer decrements in Figure 3.

Assuming that the hydrogen emission originates from an optically thick H II region obeying Case B recombination, the intrinsic Balmer flux ratios are $(H\gamma/H\beta)_0 = 0.468$ and $(H\delta/H\beta)_0 = 0.259$. Dust absorption alters these observed ratios as follows:

$$\frac{(Hn/H\beta)_{\text{obs}}}{(Hn/H\beta)_0} = 10^{-0.4E(B-V)[k(Hn)-k(H\beta)]}, \quad (1)$$

where $E(B-V)$ is the nebular color excess, and $k(\lambda) \equiv A(\lambda)/E(B-V)$ is the dust reddening curve. We illustrate in Figure 3 the observed Balmer decrements under the Calzetti et al. (2000) (hereafter Cal00) dust reddening formalism. We find that our Balmer decrements are consistent with Cal00. For the remainder of our Letter, all dust-corrected measurements adopt Cal00 reddening.

Our color excesses, are determined mostly (20/28) from $H\gamma/H\beta$. For five galaxies, we use $H\delta/H\beta$ since $H\gamma$ suffers from contamination from OH skylines. For the remaining 3 galaxies, the dust reddening could not be determined from either Balmer decrement (they were both affected by OH sky-line emission). For these galaxies, we assume $E(B-V) = 0.22 \pm 0.23$ mag ($A(H\alpha) \approx 0.73 \pm 0.75$ mag), which is the average of our sample, and is consistent with other emission-line galaxy samples (e.g., Ly et al. 2012a; Domínguez et al. 2013; Momcheva et al. 2013). For Balmer decrements that imply negative reddening (6 cases), we adopt $E(B-V) = 0$ with measurement uncertainties based on Balmer decrement uncertainties.

3.2. T_e -based Metallicity Determinations

To determine the gas-phase metallicity for our galaxies, we follow previous direct metallicity studies and use the empirical relations of Izotov et al. (2006). Here, we briefly summarize the approach, and refer readers to Ly14 for more details. First, the O^{++} electron temperature, $T_e([O III])$, can be estimated using the nebular-to-auroral [O III] ratio, $[O III] \lambda\lambda 4959, 5007 / [O III] \lambda 4363$. We correct the above flux ratio for dust attenuation (Section 3.1). We also apply a 5% correction, since T_e determinations from Izotov et al. (2006) are found to be overestimated (Nicholls et al. 2013).

Our [O III] measurements have a very large dynamic range. The strongest (weakest) [O III] $\lambda 4363$ line is 6.5% (0.7%) of the [O III] $\lambda 5007$ flux. We find that the average (median) $\lambda 4363 / \lambda 5007$ flux ratio for our sample is 0.018 (0.015). The derived T_e for our galaxy sample spans $(1-3.1) \times 10^4$ K.

To determine the ionic abundances of oxygen, we use two emission-line flux ratios, $[O II] \lambda\lambda 3726, 3729 / H\beta$ and $[O III] \lambda\lambda 4959, 5007 / H\beta$. For our metallicity estimation, we adopt a standard two-zone temperature model with $T_e([O II]) = 0.7T_e([O III]) + 3000$ (AM13), to enable direct comparisons to local studies. In computing O^+/H^+ , we also correct the $[O II]/H\beta$ ratio for dust attenuation. We do not correct $[O III]/H\beta$ since the effects are negligible.

Since the most abundant ions of oxygen in H II regions are O^+ and O^{++} , the oxygen abundances are given by $O/H = (O^+ + O^{++})/H^+$. In Table 1, we provide estimates of $T_e([O III])$, and de-reddened metallicity for our sample. Our most metal-poor systems are #04 and #08, and can be classified as extremely metal-poor galaxies ($\leq 0.1 Z_\odot$).

3.3. Dust-Corrected Star Formation Rates

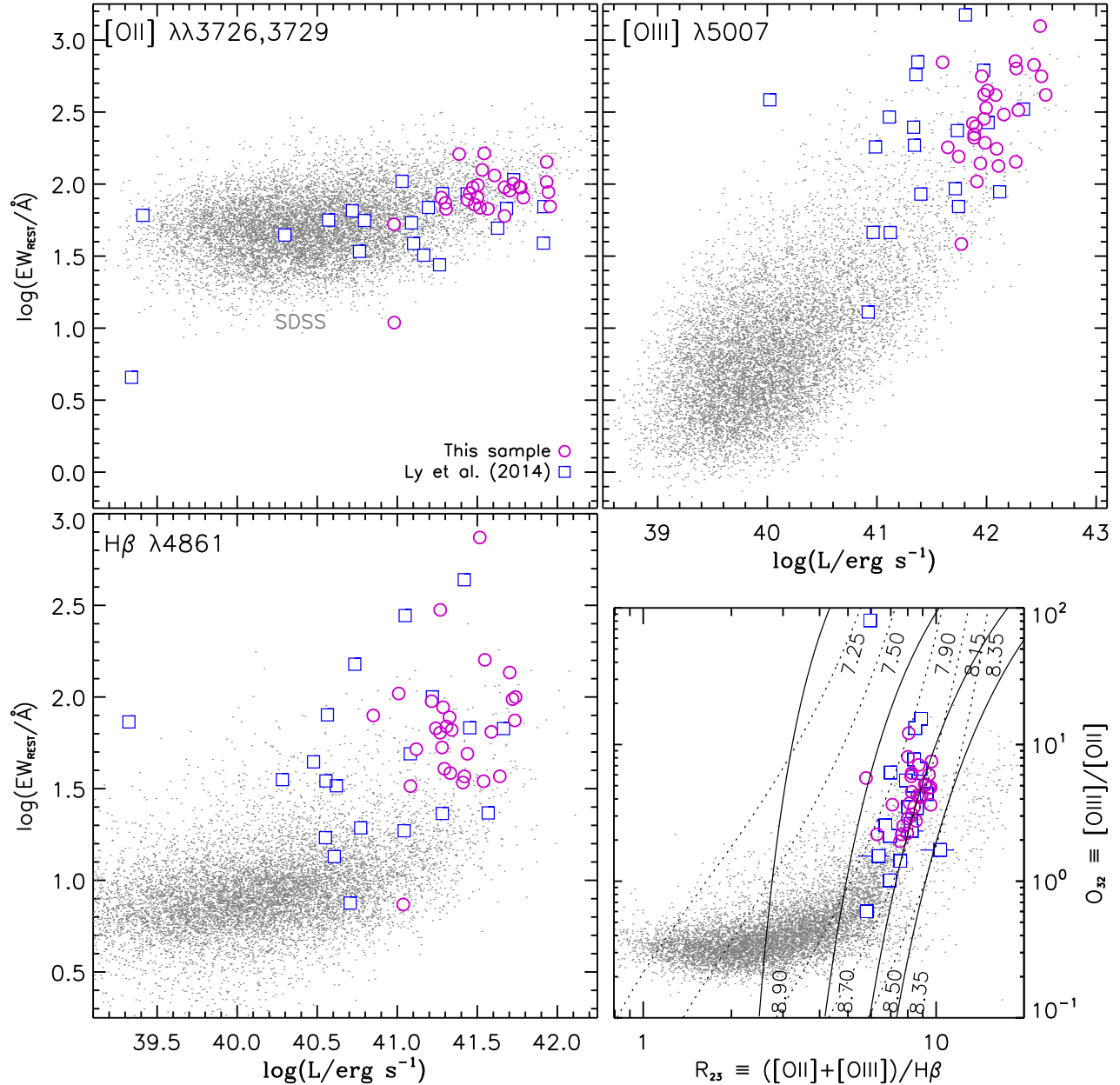


FIG. 2.— Emission-line luminosities, flux ratios, and rest-frame EWs for our [O III]λ4363 sample (purple circles). All luminosities and flux ratios are observed, before correction for dust attenuation. Gray points illustrate the SDSS DR7 emission-line sample. The lower right panel shows the metallicity-sensitive (R_{23}) and ionization parameter-sensitive (O_{32}) emission-line ratios. Photoionization models from [McGaugh \(1991\)](#) are overlaid for metallicities between $12 + \log(\text{O}/\text{H}) = 7.25$ and $12 + \log(\text{O}/\text{H}) = 8.9$. Solid (dotted) curves are for metallicities on the “upper” (“lower”) R_{23} branch. Overlaid as blue squares is the [O III]λ4363-detected sample from [Ly14](#).

In addition to gas-phase metallicity, our data allow us to determine dust-corrected SFRs using the hydrogen recombination lines, which are sensitive to the shortest timescale of star formation, $\lesssim 10$ Myr.

Assuming a [Chabrier \(2003\)](#) IMF with masses of 0.1 – $100 M_{\odot}$, and solar metallicity, the SFR can be determined from the observed $\text{H}\beta$ luminosity ([Kennicutt 1998](#)):

$$\frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}} = 4.4 \times 10^{-42} \times 2.86 \times 10^{0.4A(\text{H}\beta)} \frac{L(\text{H}\beta)}{\text{erg s}^{-1}}, \quad (2)$$

where $A(\text{H}\beta) = 4.6E(B-V)$. This relation overestimates the SFR at low metallicities due to the dependence of a stronger ionizing radiation field on lower metallicity. Since our galaxies have $Z \approx 0.2Z_{\odot}$, we reduce the SFRs

by 37% ([Henry et al. 2013b](#)). Our SFR estimates are summarized in Table 1 and are illustrated in Figure 5. We find that our galaxies have dust-corrected SFRs of 0.8 – $130 M_{\odot} \text{ yr}^{-1}$ with an average (median) of 10.7 (4.6) $M_{\odot} \text{ yr}^{-1}$.

3.4. Stellar Masses from SED Modeling

To determine stellar masses, we follow the common approach of modeling the spectral energy distribution (SED) with stellar synthesis models (e.g., [Salim et al. 2007](#); [Ly et al. 2011, 2012b](#)). The eight-band photometric data include *BRI* imaging from the Canada-France-Hawaii Telescope (CFHT) for the DEEP2 survey ([Coil et al. 2004](#)). In addition, publicly available *ugriz* imaging from the CFHT Legacy Survey is available in Field #1

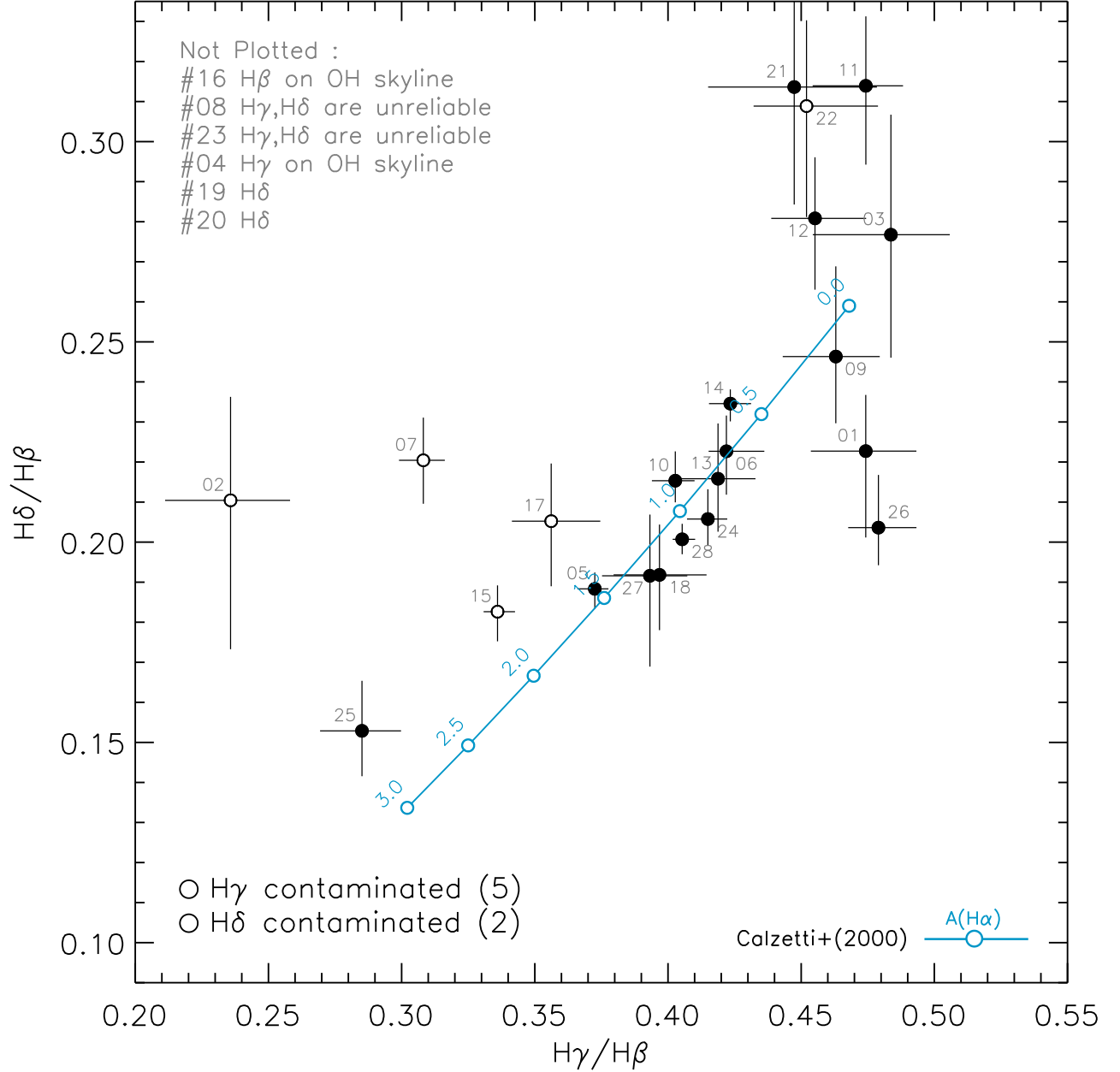


FIG. 3.— Balmer decrements ($H\gamma/H\beta$ and $H\delta/H\beta$) for our $[O III]\lambda 4363$ sample. Reliable measurements are shown by the filled circles, while those affected by contamination from OH sky-line emission are shown as open circles. Blue circles and curve show the effects on the Balmer decrements with increasing dust reddening following Calzetti et al. (2000). Values adjacent to blue circles indicate $A(H\alpha)$. The significant scatter in the upper right is due to less reliable $H\delta/H\beta$ measurements. These galaxies all have $H\gamma/H\beta$ measurements that are consistent with $A(H\alpha) \sim 0$.

(Extended Groth Strip), and Fields #3–4 are located in the SDSS deep survey strip (Stripe 82) for $u'g'r'i'z'$ imaging. Thus, 18 of 27 galaxies have eight optical imaging bands. These photometric data that we use have been compiled by Matthews et al. (2013). While our galaxies have low stellar masses (as demonstrated below), the imaging data are fairly deep. The R -band imaging, for example, reaches an 8σ AB limit of 24.5 (Newman et al. 2013), and our galaxies are on average 1.2 AB mag brighter than this limit.

To extend the wavelength coverage, we cross-matched our sample against the catalog of Bundy et al. (2006), which contains JK photometry. Unfortunately, only two galaxies have a match. This is not a surprise since many of our galaxies have low stellar masses. While photo-

metric data redward of 5500\AA are unavailable, Zahid et al. (2011) demonstrated that stellar mass estimates from BRI photometry are consistent with those obtained from $BRIK_s$, suggesting that the existing optical data are sufficient for stellar mass estimates. We also note that the lack of $ugriz$ imaging does not significantly hamper out SED modeling for 9 galaxies, as we compared stellar mass estimates derived from BRI -only and $BRI+ugriz$ photometry for two-thirds of our sample, and find consistent results. Future efforts will include acquiring *Spitzer* infrared data to provide more robust stellar mass estimates.

To model the SED, we use the Fitting and Assessment of Synthetic Templates code (Kriek et al. 2009) with Bruzual & Charlot (2003) models and adopt a Chabrier (2003) IMF, exponentially-declining star formation his-

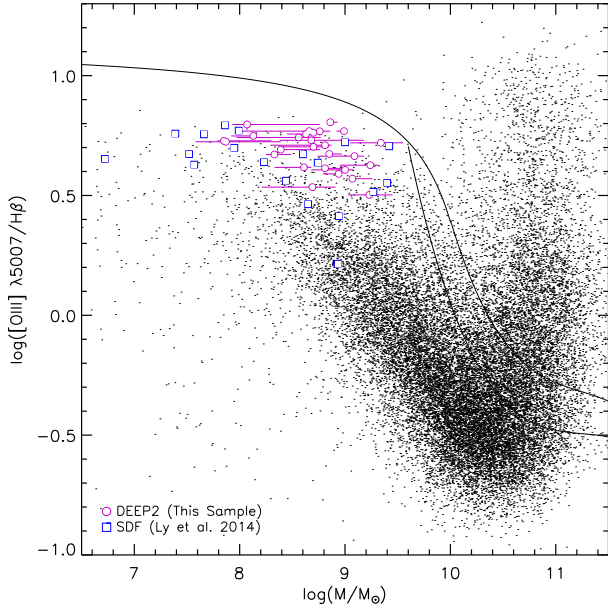


FIG. 4.— $[\text{O III}]\lambda 5007/\text{H}\beta$ flux ratio (“excitation”) as a function of stellar mass (i.e., the MEx diagram; Juneau et al. 2014). The DEEP2 $[\text{O III}]\lambda 4363$ sample is shown by the purple circles. Overlaid as blue squares is the Ly14 $[\text{O III}]\lambda 4363$ sample from the SDF. The SDSS DR7 sample is illustrated in black.

tories (SFHs; i.e., τ models), one-fifth solar metallicity, and Cal00 reddening. We also correct the broad-band photometry for the contribution of nebular emission lines following the approach described in Ly14. This correction reduces the stellar mass estimates by 0.2 dex (average). To determined stellar mass uncertainties, we conduct Monte Carlo realizations within FAST. Here, data points are randomly perturbed 100 times (based on the photometric uncertainties) and the SEDs are re-fitted, yielding a probability distribution function for stellar mass. The stellar masses are provided in Table 1 and are illustrated in Figures 4–5. The average (median) stellar masses are $4.9 \times 10^8 M_\odot$ ($5.0 \times 10^8 M_\odot$) and span 7.1×10^7 – $2.2 \times 10^9 M_\odot$.

4. RESULTS

4.1. Excitation Properties

Figure 4 illustrates the $[\text{O III}]\lambda 5007/\text{H}\beta$ flux ratios and stellar masses along the “Mass–Excitation” (MEx; Juneau et al. 2014) diagram. The MEx is used as a substitute for the Baldwin et al. (1981) diagnostic diagram when $[\text{N II}]\lambda 6583/\text{H}\alpha$ is unavailable. It can be seen that these galaxies have high $[\text{O III}]\lambda 5007/\text{H}\beta$ ratios, 5.0 ± 0.9 . All of them are classified as star-forming galaxies by falling below the solid black line. Compared to other metal-poor galaxies (Ly14, blue squares), the DEEP2 galaxies have similar excitation properties, but are ≈ 0.4 dex more massive. Compared to UV- and mass-selected $z \sim 2$ galaxies (e.g., Shapley et al. 2014; Steidel et al. 2014), our measured $[\text{O III}]\lambda 5007/\text{H}\beta$ ratios are higher by a factor of 1.25–2.5. Their strong-line oxygen ratios, R_{23} and O_{32} , are consistent with $z \sim 2$ galaxies from Shapley et al. (2014).

4.2. Relationship between Mass, Metallicity, and SFR

Figure 5(a) compares the dust-corrected instantaneous SFRs against the stellar mass estimates. Here we compare our work against mass-selected galaxies at $z \sim 1$ (Whitaker et al. 2014b) and $\text{H}\alpha$ -selected galaxies at

$z \approx 0.8$ (de los Reyes et al. 2015). Our galaxies are located 1.05 ± 0.61 dex above these M_\star –SFR relations with SFR/M_\star of $10^{-8.0 \pm 0.6} \text{ yr}^{-1}$. This significant SFR offset is also seen for metal-poor galaxies from Ly14. By requiring $[\text{O III}]\lambda 4363$ detections, both $[\text{O III}]\lambda 4363$ studies are biased toward high-EW emission lines (see Figure 2), which correspond to a higher sSFRs.

Figure 5(c) illustrates the M_\star – Z relation. Here we compare our results against AM13. It demonstrates that while a subset of our galaxies is consistent with AM13, a significant fraction (60%) are located below the relation at more than 0.22 dex (1σ ; AM13), by as much as -0.76 dex. This results in an average Z offset for the sample of -0.28 ± 0.23 dex. Our M_\star – Z relation result is consistent with Ly14 (blue squares), who also found that half of their sample falls below the local M_\star – Z relation.

The FMR was introduced to describe the dependence between M_\star , Z , and SFR in local galaxies, and was extended to explain higher redshift galaxies. Mannucci et al. (2010) was one of the first studies to parameterize this dependence by considering a combination of stellar mass and SFR:

$$\mu = \log(M_\star) - \alpha \log(\text{SFR}), \quad (3)$$

where α is the coefficient that minimizes the scatter against metallicity. Figure 5(e) illustrates the μ projection of the M_\star – Z –SFR relation with $\alpha = 0.66$ (AM13). It can be seen that our sample is consistent (0.01 ± 0.29 dex) with the local FMR; however significant dispersion remains. The dispersion is greater than our M_\star – Z comparison and the average measurement uncertainties of ≈ 0.16 dex with respect to the FMR.

The local M_\star – Z –SFR relation suggests that higher SFR galaxies have lower metallicity at fixed stellar mass. To examine if this is correct, we split our sample by high and low sSFRs, and perform Kolmogorov–Smirnov (K–S) tests to determine if these two distributions are different. These two samples are illustrated in panels (b), (d) and (f) in Figure 5 as filled (high-SFR) and open (low-SFR) symbols. The sample is divided at the median $\Delta[\log(\text{SFR})]$, which is the amount of deviation relative to the Whitaker et al. (2014a) M_\star –SFR relation. This relative SFR offset follows the non-parametric approach of Salim et al. (2014).

One concern with conducting a K–S test is the selection bias of requiring the detection of $[\text{O III}]\lambda 4363$. More specifically, detection of this line primarily depends on the electron temperature (or gas metallicity), which corresponds to the $\lambda 5007/\lambda 4363$ line ratio, and the dust-corrected SFR, which determines the overall normalization of the emission-line strengths. At high SFRs, the probability of detecting $[\text{O III}]\lambda 4363$ is greater for a wide range of metallicity. This range of metallicity reduces toward lower metallicity such that only metal-poor galaxies with low SFRs can be detected in an emission-line flux limited survey.

This selection bias is demonstrated in Figure 6, which illustrates the gas-phase metallicity as a function of dust-corrected SFR. The black curves correspond to the average $[\text{O III}]\lambda 4363$ S/N=3 detection limit of $3.4 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$. This limit was determined from measuring the rms in 4,140 spectra in areas adjacent to where $[\text{O III}]\lambda 4363$ is expected to be detected. In determining the metallicity–SFR dependence, we consider (1) an ionic

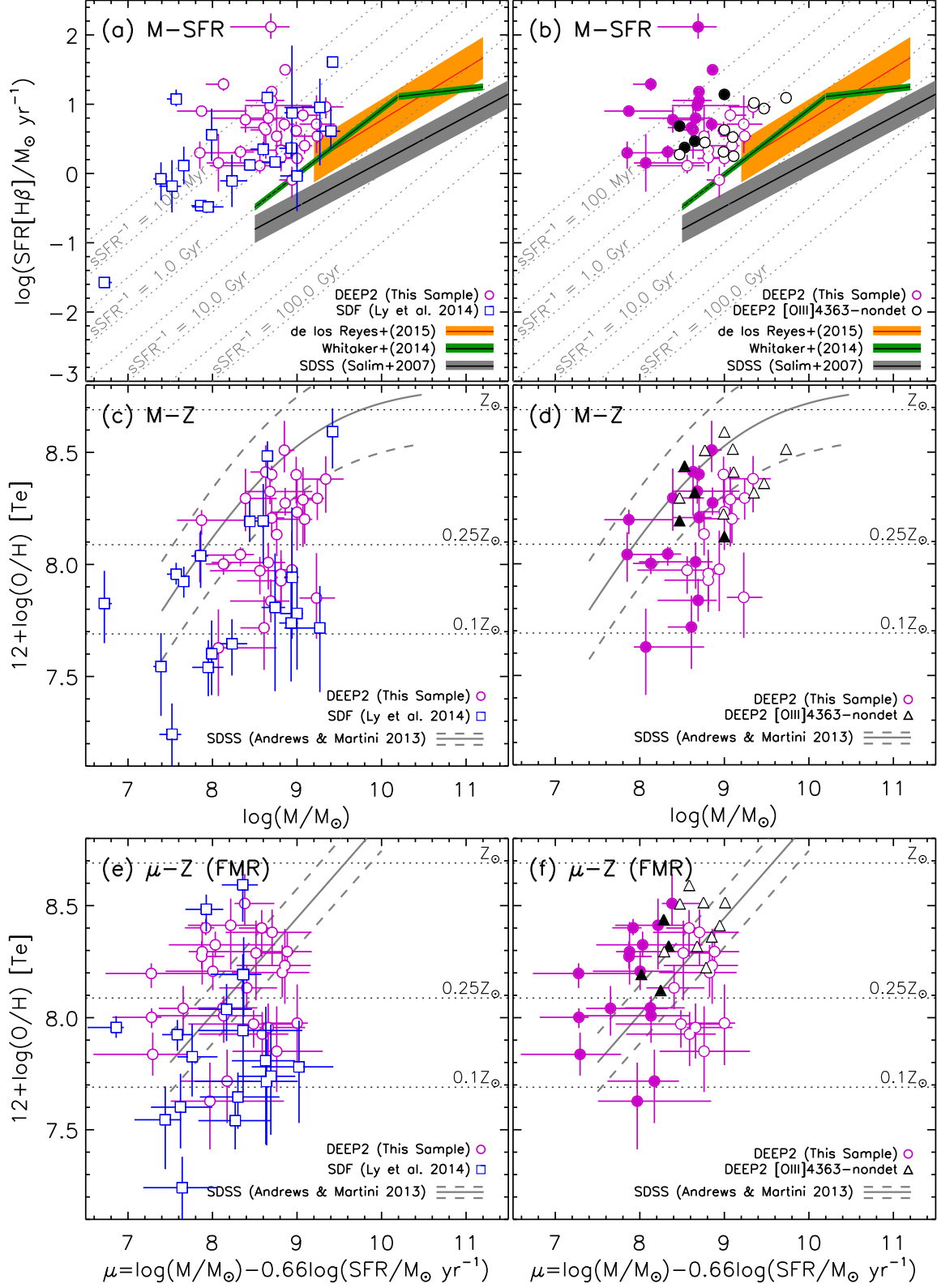


FIG. 5.— Relations between stellar mass and (top) dust-corrected H β SFR, (middle) metallicity, and (bottom) metallicity and dust-corrected H β SFR (i.e., the FMR). The DEEP2 [O III] λ 4363 sample is shown by the purple circles. Overlaid as blue squares on the left panels is the Ly14 [O III] λ 4363 sample from the SDF. Results from the SDSS sample (Salim et al. 2007; AM13) is illustrated in gray. For comparisons, we also overlay in the top panels the stellar mass-SFR relation of H α -selected galaxies at $z = 0.8$ (de los Reyes et al. 2015) and mass-selected star-forming galaxies at $z = 0.5$ –1 (Whitaker et al. 2014a) in orange and green, respectively. For direct metallicity comparisons, we illustrate the results of AM13, which stacked spectra to measure average T_e -based metallicities. DEEP2 galaxies with reliable non-detections of [O III] λ 4363 are shown as black circles and triangles (lower limit on metallicity). The DEEP2 samples are separated by low and high SFRs (see text) as open and filled symbols, respectively.

oxygen abundance ratio (O^{++}/O^+) of unity, which is the average for our DEEP2 $[O\text{ III}]\lambda 4363$ sample, and (2) a temperature–metallicity relation of $12 + \log(O/H) = 9.51 - 1.03(T_e/10^4 \text{ K})$. The latter is empirically determined from our DEEP2 $[O\text{ III}]\lambda 4363$ galaxies.

To account for the Z –SFR selection bias, we include reliable $[O\text{ III}]\lambda 4363$ non-detections within our K-S analyses. First, we consider all DEEP2 galaxies with $S/N \geq 100$ on $[O\text{ III}]\lambda 5007$ and a non-detection ($S/N < 3$) on $[O\text{ III}]\lambda 4363$. This sample of 126 galaxies is then vetted for unreliable limits because the $[O\text{ III}]\lambda 4363$ emission line either falls on an OH skyline, the atmospheric A-band, or a CCD gap. This limited the sample to 79 galaxies. While the above $[O\text{ III}]\lambda 5007$ S/N cut is strict, for many of these galaxies, a strong lower limit on the metallicity is not available. This is because a $S/N=100$ corresponds roughly to 0.03 on $\lambda 4363/\lambda 5007$ or $T_e \approx 2 \times 10^4$ K. Thus, we further restrict our non-detection sample to 13 galaxies with $[O\text{ III}]\lambda 5007$ $S/N \geq 200$. These galaxies are overlaid in Figure 6 and panels (b), (d), and (f) in Figure 5 as either black circles or black triangles ($S/N=3$ lower limit on metallicity). It can be seen that the majority of these galaxies are located to the left of the $S/N=3$ line for $E(B-V) = 0.22$ mag in Figure 6. Also, Figure 5 illustrates that these galaxies have higher stellar masses (0.3 dex) than our detected sample, and lower SFRs at a given stellar mass. As expected, these galaxies have higher metallicity with lower limits above $12 + \log(O/H) \approx 8.2$ (average: 8.37).

For our K-S tests, we compare the $\log(O/H)$ distributions for the low- and high-SFR samples, finding that these two distributions are similar with the lower SFR galaxies having slightly higher metallicity (see Figure 7(a)). However, as Figure 5(b) shows, these two samples differ in stellar mass by ≈ 0.5 dex. If instead we consider the relative offset in metallicity against the M_\star – Z relation of AM13, the K-S test finds that the two samples are different at 94.4% (1.9σ ; Figure 7(b)). The difference, however, is in the opposite direction of local predictions, with higher sSFR galaxies having higher gas-phase metallicities.

Given this discrepancy, it is also important to investigate whether the same result is seen when considering the FMR that Mannucci et al. (2010) defined. Here, they utilized the R_{23} strong-line diagnostic and a fourth-order polynomial for R_{23} – Z (Maiolino et al. 2008). However, the majority of our DEEP2 sample have dust-corrected R_{23} values that exceed the maximum threshold value of $R_{23} = 8.65$. Thus, it is not possible to conduct the same K-S test analysis with R_{23} and the Maiolino et al. (2008) calibration.

5. DISCUSSIONS

From DEEP2 spectra of 28 galaxies with oxygen abundances from $[O\text{ III}]\lambda 4363$ detections (i.e., the T_e method), we find that metal-poor strongly star-forming galaxies are consistent with the local FMR (AM13), albeit with large dispersion (0.29 dex with 0.16 dex due to measurement errors). This result is consistent with metal-poor galaxies from Ly et al. (2014), and lensed low-mass star-forming galaxies at $z \sim 0.8$ – 2.6 (Wuyts et al. 2012). Given the high sSFRs of $\sim (100 \text{ Myr})^{-1}$, we argue that the large dispersion in metallicity is unsurprising—these galaxies are most likely undergoing episodic star forma-

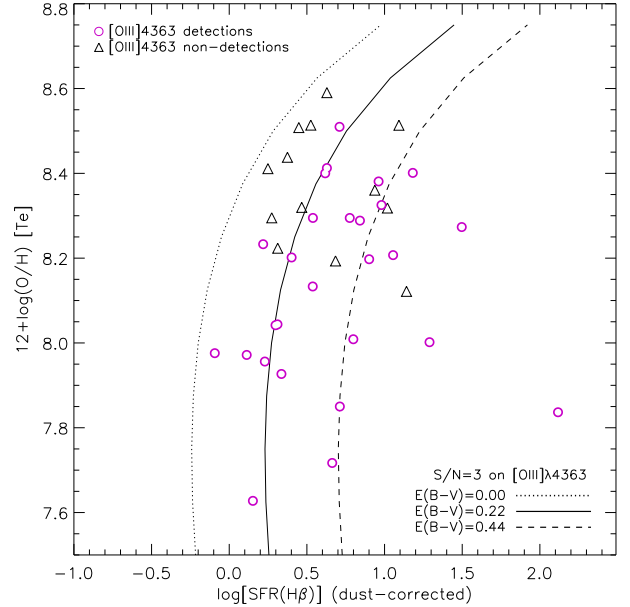


FIG. 6.— Gas-phase metallicity as a function of dust-corrected SFR for our $[O\text{ III}]\lambda 4363$ sample (purple circles) and a sample of reliable $[O\text{ III}]\lambda 4363$ non-detections at $S/N < 3$ (black triangles). The triangles are lower limits on metallicity. The dotted, solid, and dashed lines correspond to a $S/N=3$ limit on $[O\text{ III}]\lambda 4363$ of $3.4 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ for three dust extinction possibilities, $E(B-V) = 0.0, 0.22$, and 0.44 , respectively. These extinction values span the dispersion seen in our sample.

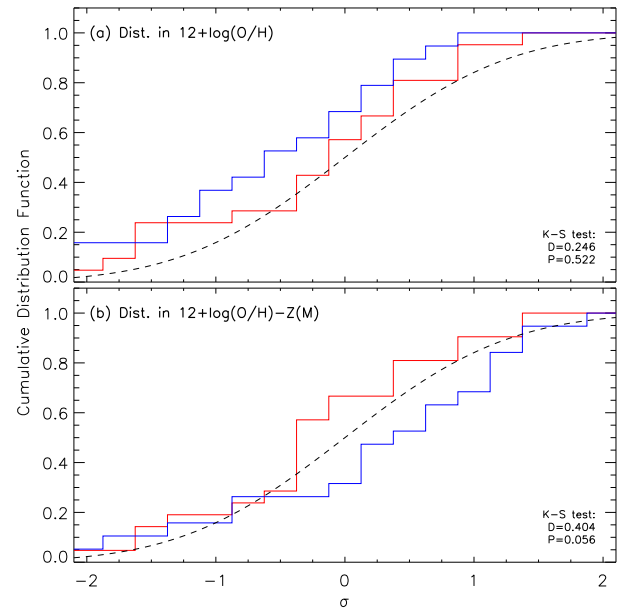


FIG. 7.— Cumulative distribution functions in (a) metallicity and (b) metallicity relative to the AM13 M_\star – Z relation, for two samples with low (red line) and high SFRs (blue line). The K-S statistics (D) and the probability that the two distributions are identical (P) are given in the lower right-hand corner. Panel (b) shows that the two distributions are different at 94.4% confidence.

tion and have not settled into a steady state.

We find marginal (94.4%; 1.9σ) evidence that galaxies with higher sSFRs ($\lesssim 10^{-8} \text{ yr}^{-1}$) are more metal-rich. While this contradicts previous local studies, the inverse of the sSFR—timescale for star formation—is short. Assuming outflow velocities comparable to virial velocities ($\sim 150 \text{ km s}^{-1}$) for $\log(M_{\text{halo}}/M_\odot) \approx 11.1$ (Behroozi

et al. 2010), 8 galaxies in our sample would not have enough time ($\text{sSFR}^{-1} \lesssim 10^{7.65} \text{ yr}$) for any recently enriched outflows to be driven out of the $1''$ (7.5 kpc) slit-widths. Thus, one would expect the $\text{SFR}-Z$ dependence to turn positive for low-mass strongly star-forming galaxies. Given the instantaneous SFRs, we find that the measured oxygen abundances can be explained with low nucleosynthesis yields ($y \sim 0.01$), gas-to-stellar mass fraction of $\approx 1 \pm 0.4$, and no metal loss due to outflows.

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TABLE 1
SUMMARY OF DEEP2 SAMPLE

ID	R.A. (hh:mm:ss)	Declination (dd:mm:ss)	z	EW(H β) (Å)	$\log(M_*/M_\odot)$	$\log\left[\frac{\text{SFR}_{\text{H}\beta}}{M_\odot \text{ yr}^{-1}}\right]$	$E(B-V)$ (mag)	S/N ($\lambda 4363$)	[O II]/H β	[O III]/H β	$\frac{[\text{O III}]}{[\text{O II}] \lambda 4363}$	$\log(T_e/\text{K})$	$12 + \log(\text{O}/\text{H})$
01	14:18:31.260	52:49:42.545	0.8194	38.46	$8.81^{+0.18}_{-0.00}$	0.23 ± 0.16	$0.00^{+0.09}_{-0.08}$	4.9	$2.165^{+0.101}_{-0.051}$	$5.507^{+0.156}_{-0.067}$	$57.273^{+11.748}_{-08.811}$	4.18 ± 0.04	$7.96^{+0.11}_{-0.14}$
02	14:21:21.513	53:01:07.672	0.7496	51.94	$8.76^{+0.04}_{-0.06}$	$0.54^{+0.45}_{-0.33}$	$0.28^{+0.24}_{-0.18}$	5.9	$1.821^{+0.705}_{-0.235}$	$7.792^{+0.200}_{-0.351}$	$67.843^{+19.856}_{-06.619}$	4.14 ± 0.04	8.13 ± 0.10
03	14:21:25.487	53:09:48.071	0.7099	104.49	$8.94^{+0.00}_{-0.15}$	$-0.09^{+0.19}_{-0.25}$	$0.00^{+0.10}_{-0.14}$	3.7	2.413 ± 0.103	$5.178^{+0.198}_{-0.085}$	$54.985^{+20.947}_{-10.473}$	$4.17^{+0.06}_{-0.05}$	$7.98^{+0.17}_{-0.19}$
04	14:22:03.718	53:25:47.766	0.7878	7.38	...	$-0.06^{+0.63}_{-0.59}$	$0.00^{+0.34}_{-0.32}$	5.5	0.867 ± 0.094	$7.273^{+0.385}_{-0.578}$	$18.192^{+05.923}_{-01.692}$	$4.49^{+0.08}_{-0.07}$	$7.35^{+0.11}_{-0.17}$
05	14:21:45.408	53:23:52.699	0.7710	74.51	$8.86^{+0.07}_{-0.00}$	$1.50^{+0.07}_{-0.05}$	$0.47^{+0.04}_{-0.03}$	10.0	1.960 ± 0.084	$8.497^{+0.080}_{-0.053}$	$90.482^{+10.167}_{-08.133}$	4.10 ± 0.02	$8.27^{+0.07}_{-0.06}$
06	16:47:26.188	34:45:12.126	0.7166	36.91	$8.85^{+0.12}_{-0.01}$	$0.71^{+0.07}_{-0.10}$	$0.21^{+0.04}_{-0.05}$	5.0	$2.539^{+0.221}_{-0.095}$	6.245 ± 0.081	$131.237^{+47.723}_{-15.908}$	$4.02^{+0.02}_{-0.03}$	$8.51^{+0.13}_{-0.10}$
07	16:46:35.420	34:50:27.928	0.7624	34.71	$9.07^{+0.19}_{-0.00}$	$0.84^{+0.12}_{-0.10}$	$0.22^{+0.07}_{-0.05}$	3.4	$3.304^{+0.208}_{-0.260}$	$5.003^{+0.040}_{-0.081}$	$83.493^{+25.690}_{-12.845}$	4.09 ± 0.05	$8.29^{+0.15}_{-0.21}$
08	16:47:26.488	34:54:09.770	0.7653	79.33	$8.07^{+0.69}_{-0.14}$	0.15 ± 0.42	0.22 ± 0.23	4.0	$1.412^{+0.779}_{-0.097}$	$7.866^{+0.589}_{-0.168}$	$24.249^{+08.434}_{-04.217}$	$4.38^{+0.08}_{-0.11}$	$7.63^{+0.17}_{-0.21}$
09	16:49:51.368	34:45:18.210	0.7909	53.06	$9.00^{+0.08}_{-0.32}$	$0.22^{+0.17}_{-0.12}$	$0.02^{+0.09}_{-0.07}$	3.6	$2.496^{+0.197}_{-0.079}$	$5.485^{+0.124}_{-0.099}$	$78.655^{+29.964}_{-14.982}$	$4.10^{+0.05}_{-0.04}$	$8.23^{+0.16}_{-0.17}$
10	16:51:31.472	34:53:15.964	0.7945	64.52	$8.70^{+0.15}_{-0.31}$	1.06 ± 0.08	0.31 ± 0.04	6.4	$2.159^{+0.093}_{-0.140}$	$6.739^{+0.094}_{-0.040}$	$85.109^{+15.474}_{-12.379}$	$4.11^{+0.02}_{-0.03}$	$8.21^{+0.09}_{-0.08}$
11	16:50:55.342	34:53:29.875	0.7980	94.85	$8.56^{+0.21}_{-0.59}$	$0.11^{+0.16}_{-0.11}$	$0.00^{+0.08}_{-0.06}$	7.7	2.086 ± 0.065	$7.480^{+0.148}_{-0.118}$	$58.301^{+03.195}_{-11.181}$	4.19 ± 0.03	$7.97^{+0.06}_{-0.11}$
12	16:53:03.486	34:58:48.946	0.7488	69.05	$8.33^{+0.16}_{-0.08}$	$0.31^{+0.10}_{-0.15}$	$0.06^{+0.05}_{-0.08}$	13.2	$1.702^{+0.229}_{-0.000}$	$6.384^{+0.130}_{-0.056}$	$70.872^{+04.765}_{-05.956}$	$4.15^{+0.02}_{-0.01}$	$8.04^{+0.03}_{-0.05}$
13	16:51:24.060	35:01:38.740	0.7936	32.65	$9.09^{+0.09}_{-0.35}$	$0.40^{+0.17}_{-0.12}$	$0.23^{+0.09}_{-0.06}$	5.2	$2.862^{+0.369}_{-0.185}$	$6.241^{+0.154}_{-0.103}$	$74.343^{+15.250}_{-11.437}$	$4.13^{+0.03}_{-0.04}$	$8.20^{+0.12}_{-0.11}$
14	16:51:20.343	35:02:32.628	0.7936	135.97	$8.68^{+0.50}_{-0.30}$	$0.98^{+0.08}_{-0.06}$	0.21 ± 0.04	9.3	2.173 ± 0.089	7.209 ± 0.040	$105.147^{+12.086}_{-09.669}$	$4.07^{+0.01}_{-0.02}$	8.33 ± 0.06
15	23:27:20.369	00:05:54.762	0.7553	741.71	$8.13^{+0.01}_{-0.21}$	$1.29^{+0.09}_{-0.10}$	0.48 ± 0.05	13.6	$1.034^{+0.096}_{-0.027}$	$7.428^{+0.084}_{-0.042}$	$72.096^{+04.614}_{-06.921}$	$4.15^{+0.01}_{-0.02}$	$8.00^{+0.04}_{-0.05}$
16	23:27:43.140	00:12:42.832	0.7743	34.15	$9.23^{+0.22}_{-0.20}$	0.71 ± 0.42	0.22 ± 0.23	3.4	$1.958^{+0.945}_{-0.000}$	4.320 ± 0.124	$46.844^{+18.738}_{-12.492}$	4.21 ± 0.07	$7.85^{+0.20}_{-0.18}$
17	23:27:29.854	00:14:20.439	0.7637	40.62	$8.39^{+0.37}_{-0.01}$	0.78 ± 0.19	0.32 ± 0.10	4.3	$2.420^{+0.596}_{-0.074}$	$6.508^{+0.147}_{-0.074}$	$89.583^{+28.898}_{-17.339}$	4.09 ± 0.04	$8.29^{+0.13}_{-0.15}$
18	23:27:07.500	00:17:41.503	0.7885	49.03	$9.34^{+0.21}_{-0.29}$	$0.96^{+0.14}_{-0.17}$	$0.34^{+0.08}_{-0.09}$	4.4	$1.794^{+0.129}_{-0.194}$	7.022 ± 0.113	$115.500^{+37.258}_{-14.903}$	4.04 ± 0.04	$8.38^{+0.10}_{-0.15}$
19	23:26:55.430	00:17:52.919	0.8562	97.37	$8.99^{+0.00}_{-0.07}$	$0.62^{+0.13}_{-0.08}$	$0.00^{+0.07}_{-0.04}$	5.2	$1.636^{+0.021}_{-0.026}$	$7.989^{+0.066}_{-0.132}$	$128.952^{+17.993}_{-23.991}$	$4.04^{+0.03}_{-0.02}$	$8.40^{+0.08}_{-0.13}$
20	23:30:57.949	00:03:38.191	0.7842	87.95	$8.61^{+0.07}_{-0.28}$	$0.66^{+0.18}_{-0.26}$	$0.26^{+0.10}_{-0.14}$	4.1	$2.017^{+0.276}_{-0.221}$	$5.575^{+0.132}_{-0.159}$	$36.499^{+14.600}_{-05.840}$	$4.26^{+0.05}_{-0.09}$	$7.72^{+0.14}_{-0.19}$
21	23:31:50.728	00:09:39.393	0.8225	63.83	$8.81^{+0.06}_{-0.52}$	$0.34^{+0.29}_{-0.30}$	$0.09^{+0.16}_{-0.17}$	5.0	$1.692^{+0.344}_{-0.115}$	$6.989^{+0.179}_{-0.223}$	$52.462^{+11.343}_{-08.507}$	$4.19^{+0.05}_{-0.04}$	$7.93^{+0.10}_{-0.14}$
22	02:27:48.871	00:24:40.077	0.7838	298.74	$7.85^{+0.45}_{-0.06}$	$0.30^{+0.16}_{-0.23}$	$0.07^{+0.09}_{-0.13}$	5.3	$1.735^{+0.343}_{-0.043}$	$7.110^{+0.103}_{-0.207}$	$61.688^{+12.654}_{-09.490}$	$4.16^{+0.03}_{-0.04}$	$8.04^{+0.10}_{-0.12}$
23	02:27:05.706	00:25:21.865	0.7661	77.52	$8.63^{+0.07}_{-0.18}$	0.63 ± 0.42	0.22 ± 0.23	3.2	$1.492^{+0.720}_{-0.000}$	$7.631^{+0.135}_{-0.108}$	$144.017^{+00.000}_{-57.607}$	$4.05^{+0.05}_{-0.06}$	$8.41^{+0.12}_{-0.20}$
24	02:27:30.457	00:31:06.391	0.7214	159.58	$7.87^{+0.52}_{-0.29}$	$0.90^{+0.07}_{-0.06}$	0.25 ± 0.04	9.6	1.525 ± 0.076	7.105 ± 0.057	$94.916^{+08.344}_{-10.430}$	4.09 ± 0.02	$8.20^{+0.05}_{-0.06}$
25	02:26:03.707	00:36:22.460	0.7888	66.11	$8.69^{+0.22}_{-0.48}$	$2.12^{+0.20}_{-0.17}$	$1.02^{+0.11}_{-0.09}$	6.6	$2.857^{+0.269}_{-0.336}$	$4.878^{+0.130}_{-0.065}$	$48.598^{+05.116}_{-08.526}$	$4.23^{+0.04}_{-0.03}$	$7.84^{+0.10}_{-0.09}$
26	02:26:21.479	00:48:06.813	0.7743	36.94	$9.24^{+0.08}_{-0.29}$	0.54 ± 0.10	$0.00^{+0.05}_{-0.06}$	6.7	$2.064^{+0.031}_{-0.041}$	$5.895^{+0.089}_{-0.044}$	$109.091^{+0.089}_{-14.307}$	4.07 ± 0.02	$8.29^{+0.08}_{-0.10}$
27	02:29:33.654	00:26:08.023	0.7294	67.55	$8.66^{+0.20}_{-0.67}$	$0.80^{+0.14}_{-0.20}$	$0.36^{+0.08}_{-0.11}$	7.0	$2.555^{+0.220}_{-0.330}$	$7.849^{+0.132}_{-0.231}$	$54.969^{+09.644}_{-07.715}$	4.19 ± 0.04	$8.01^{+0.09}_{-0.12}$
28	02:29:02.031	00:30:08.127	0.7315	99.97	$8.70^{+0.01}_{-0.06}$	$1.18^{+0.03}_{-0.04}$	0.30 ± 0.02	15.2	$1.515^{+0.042}_{-0.028}$	$7.633^{+0.037}_{-0.019}$	$132.444^{+10.667}_{-05.333}$	4.04 ± 0.01	$8.40^{+0.04}_{-0.03}$

NOTE. — Unless otherwise specified, [O III] refers to [O III] $\lambda\lambda 4959, 5007$.